

Method and device for using a multi-channel measurement signal  
in determining the current distribution of an object

#### FIELD OF THE INVENTION

The present invention relates to a new and advanced method for using a multi-channel measurement signal in source modelling. In particular, the present invention relates to a new way of converting the measurement signals measured using a multi-channel measuring device that measures an irrotational and sourceless vector field into a form optimal from the standpoint of the source modelling.

#### BACKGROUND OF THE INVENTION

The electrical operation of an object to be examined can be examined e.g. by measuring the magnetic field produced by the electric currents of the object using sensors placed outside the object. The modelling of a source distribution thus obtained based on the measured signals is, however, very difficult because each magnetic field distribution can be produced by many different source distributions. In other words, a source distribution cannot be solved unambiguously based on the measured signals, so to solve the problem, different restrictive conditions must be set, such as some parametric model based on prior information for a current, or a non-parametrised norm restriction.

For the non-parametrised modelling of a continuous current distribution, minimum norm estimates are usually used, in which there is an attempt to explain a signal measured using a multi-channel measurement device with a current distribution whose norm is as small as possible. As the norm, usually an L1 or L2 norm is selected, of which the previous is the sum of the lengths of the current elements over the selected

volume, and the latter is the sum of the squares of the lengths of the current elements over the selected volume. The calculation of the minimum norm estimates has been described e.g. in publications "Interpreting magnetic fields of the brain: minimum norm estimates", M.S. Hämäläinen et al, Medical & Biological Engineering & Computing, Vol. 32, pp. 35-42, 1994, as well as "Visualization of magnetoencephalographic data using minimum current estimates", Uutela K. et al, NeuroImage, Vol. 10, pp. 173-180, 1999.

Conventional minimum norm estimates involve inherent problems such as slowness of calculation and susceptibility to noise. For example, in the case of an L2 norm, one needs an inverse matrix of matrix  $G$ , whose element  $(i, j)$  contains the inner product of the switching fields of the  $i$ th and  $j$ th measurement sensor, so one must calculate these inner products for each pair of sensors. The switching field is so determined that the signal measured by a sensor is the projection of the current distribution for the switching field of the sensor in question. The noise problems are due to the fact that matrix  $G$  calculated for the sensors is susceptible to noise, so in the calculation of its inverse matrix, regularisation is needed in the practical situations.

Regularisation methods, such as the break-off regularisation of the singular value decomposition, usually are non-intuitive, and usually also to be solved for each case specifically. A regularisation of the wrong type may lead to an erroneous modelling result.

Therefore, source modelling nowadays still involve problems such as the hardness and slowness of the computation, the possible errors caused by noise, as well as the case-specificity due to the regularisation. Further, as stated above, the regularisation may

cause considerably errors to the final computation result.

#### OBJECTIVE OF THE INVENTION

The objective of the invention is to eliminate the drawbacks referred to above, or at least significantly to alleviate them. One specific objective of the invention is to disclose a new type of method which can be used to considerably lighten and accelerate the computation associated with the modelling of a continuous current distribution, as well as to lessen the problems with noise.

As for the features characteristic of the invention, reference is made to them in the claims.

#### DESCRIPTION OF THE INVENTION

The present invention relates to a new kind of manner of determining the continuous current distribution of an object being examined using basis vector components of signal space calculated from the measured signals. The components in question have been so selected that they describe the features, as independent as possible, of the current distribution being examined, which enhances the computation and makes it more accurate.

The basic idea of the invention is that because the computation of the inner products of the sensor fields is hard and difficult using a conventional set of sensors, it is worth using a special set of sensors, whose switching fields are orthogonal and, if possible, to be analytically computed. In principle, this can be implemented by a suitable physical set of sensors. As a suitable physical set of sensors is, however, often quite difficult to manufacture, it is, in most of the cases, advantageous to use virtual sensors computationally generated from a conventional

set of sensors, i.e. the measurement signals are converted into other ones by a suitable conversion so that they correspond to the signals that the virtual measurement device would have measured. At the same time, it is possible, if necessary, to eliminate the signals associated with external interference. This conversion has been described e.g. in patent application FI20030392, which is incorporated herein by reference. After the conversion, the source modelling is performed in an optimal manner using the basis vector components of the signal space instead of the actual measurement signals. One substantial feature of the invention is that after the conversion, the source model need not be any more regularised.

Thus, the present invention relates to a method for determining the current distribution of an object by measuring the magnetic fields in the vicinity of the object using a multi-channel measurement device. Advantageously, at least one measurement sensor corresponds to each channel, and the object is approximated by a spherical-symmetrical conductor. The object can be e.g. a human being's head.

According to the invention, a multi-channel measurement signal corresponding to each measurement sensor is converted into the signals of a predetermined set of virtual sensors, and the current distribution of the object being examined is determined by depth  $r$  from the signals of the set of virtual sensors in a beforehand selected orthonormal function basis. In that case, the estimation of a current distribution is fast and robust. Further, to achieve the set of signals corresponding to the set of virtual sensors, a multi-pole development is calculated from a multi-channel measurement signal. A multi-pole development can be calculated in two ways: by taking into account the magnetic fields outside the object being measured, or by ignoring them.

Advantageously, as the orthonormal function basis, a basis with the following form is selected:

$$j(\mathbf{r}) = \sum_{l=0}^L \sum_{m=-l}^l c_{lm} f(r) Y_{lm}(\theta, \varphi),$$

wherein  $f(r)$  is a radial function to be freely selected and  $Y_{lm}(\theta, \varphi)$  is so-called vector spherical harmonic. In that case, it is possible to place the function basis into a current distribution equation, and the coefficients of the current distribution are analytically solved based on the equation:

$$c_{lm} = \gamma_l M_{lm} \left[ \int_0^R r' f(r) dr \right]^{-1},$$

wherein  $\gamma_l$  is a constant associated with order  $l$  and  $R$  is the radius of the sphere to be examined. Advantageously, function  $f(r)$  is used to adjust the depth weighing of a current distribution model.

Furthermore, the invention relates to a measurement device for determining the current distribution by measuring magnetic fields in the vicinity of the object. The measurement device includes a set of measurement channels that measure an irrotational and sourceless vector field, whereby at least one measurement sensor corresponds to each channel, and processing means for processing the measurement signal. Advantageously, the object is approximated with a spherical-symmetrical conductor.

According to the invention, the processing means include a conversion module for converting a multi-channel measurement signal corresponding to each measurement sensor into the signal of a predetermined set of virtual sensors; and calculation means for determining the current distribution of an object being examined or for calculating by depth  $r$  from the sig-

nals of the set of virtual sensors in a beforehand selected orthonormal function basis. In one embodiment, the calculation means are arranged to calculate a multi-pole development from a multi-channel measurement signal.

The invention enables one to considerably lighten and accelerate the calculation associated with the modelling of a continuous current distribution. The invention further enables one to reduce the problems associated with noise. Further, the invention simplifies the regularisation of a source model, or eliminates the need for it, thus also significantly reducing the possibility of error.

#### LIST OF FIGURES

In the following, the invention will be described in detail by means of examples with reference to the accompanying drawing, in which

Fig. 1 represents one measurement device in accordance with the present invention; and

Fig. 2 is a flow chart illustrating one method in accordance with the present invention.

#### DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 represents one measurement device in accordance with the present invention comprising a set of measurement channels  $1^1, 1^2, \dots, 1^5$  that measure an irrotational and sourceless vector field, in which case at least one measurement sensor  $2^1, 2^2, \dots, 2^5$  corresponds to each channel; and processing means 3 for processing the measurement signal. Advantageously, the processing means have been implemented by means of a computer. Further, the processing means include a conversion module 4 for converting a multi-channel measurement signal corresponding to each measurement sensor into the signals of a predetermined set of virtual

sensors, and calculation means 5 for determining the current distribution of an object being examined.

Further Fig. 1 shows the object being measured K, into the vicinity of which the measurement sensors  $2^1, 2^2, \dots, 2^5$  have been placed. Inside the object being measured there is presented a current loop which describes the source of the magnetic field being measured. The object being measured can be e.g. a human head, and there can be several current sources.

Fig. 2 represents the main steps of one preferred embodiment of the present invention. At first, a set of sensors is used to measure a multi-channel measurement signal, step 21. After that, the signal is converted to correspond to the signal measured using a so-called set of virtual sensors, step 22, making the mathematical operations simpler. Finally, it is possible to simply calculate the current distribution in an object from the signal of the set of virtual sensors, step 23, i.e. in practice, to describe the places and strengths of the current loops inside a sphere or head.

In the following section, the mathematical background and grounds of the invention are described. When the magnetic fields are converted into coefficients  $M_{lm} = a_{lm} + ib_{lm}$  associated with the basic solution  $r^{-(l+1)}Y_{lm}(\theta, \varphi)$  of the Laplace equation, wherein  $i$  is an imaginary unit, they can be expressed by means of the current distribution  $J(\vec{r})$  in spherical coordinates  $(r, \theta, \varphi)$ , whereby they are of the form:

$$M_{lm} = \gamma_l \int_V r'^l X_{lm}(\theta, \varphi) \cdot J(\vec{r}) dV \quad (1),$$

wherein the integration is performed over the volume being examined,  $\gamma_l$  is a constant associated with order  $l$  and  $X_{lm}(\theta, \varphi)$  is so-called vector spherical harmonic.

This form is apparent e.g. from publication "Multipole expansions of electromagnetic fields using Debye potentials", C.G. Gray, American Journal of Physics, Vol. 46, pp. 169-179, 1978. The expression mentioned above is of the switching field form, wherein the switching field of the multi-pole coefficient  $M_{lm}$  is of the form:

$$E_{lm}(\beta) = r^l X_{lm}^p(\theta, \varphi) \quad (2).$$

On the other hand, the vector spherical harmonics form by depth  $r$  an orthonormal basis, so with the depth in question, the current distribution can be presented in the function basis in question:

$$J(\beta) = \sum_{l=0}^L \sum_{m=-l}^l c_{lm} f(r) X_{lm}^p(\theta, \varphi) \quad (3),$$

wherein  $f(r)$  is some radical function.

When as the volume to be examined, spherical volume is selected, by placing the previous expression into the equation (1), the coefficients of the current distribution can be analytically solved:

$$c_{lm} = \hat{\gamma}_l M_{lm} \left[ \int_0^R r^l f(r) dr \right]^{-1} \quad (4),$$

wherein  $\hat{\gamma}_l$  is a constant associated with order  $l$  and  $R$  is the radius of the sphere to be examined. The previous equation (4) indicates that the coefficients of a current distribution model presented in an orthonormal basis can be solved based on coefficients  $M_{lm}$  in a completely trivial manner using analytical expressions without any kind of regularisation. This is computationally very fast and numerically stable. Function  $f(r)$  is freely selectable, and



can be used to adjust the depth weighing of a current distribution model.

Furthermore, it must be noted that in the case of a spherical conductor, it is possible to use as basis functions also some other orthogonal basis or a basis whose inner products can be otherwise quickly calculated. This is achieved e.g. by slightly breaking the orthogonality in a manner known per se, or by using a basis which is not orthogonal but whose inner products can be calculated beforehand.

The invention is not limited merely to embodiment examples referred to above, instead many variations are possible within the scope of the inventive idea defined by the claims.